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FINAL TECHNICAL REPORT

Analytical Exponential Decay Coefficients
and
Internal Radiant Emission Phenomena
of the
Submarine Light Field

ONR *Contract Number:*   N00014-86-K-0606

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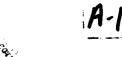919-334-5391

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Introduction

I wish to report on the research accomplishments during the three year tenure of ONR Contract No. N00014-86-K-0606 which was originally for a two year period and then extended one more year. The contract period started with a one year Research Leave from the University of North Carolina at Greensboro, jointly sponsored by the university and ONR. The first four months of the contract period were spent as a Visiting Professor at the University of Southern California and the rest of the first contract year was spent as a Visiting Professor at Naval Ocean Research and Development Activity (now Naval Ocean and Atmospheric Research Laboratories), Bay St. Louis, Mississippi. The second year of the contract involved full-time academic duties at the University of North Carolina at Greensboro continuing the collaboration with NORDA. The third year of the contract involved residence at the University of North Carolina at Greensboro with the summer spent at NORDA.

Contract Period 1986 - 1987

The initial period under this contract was spent primarily at the University of Southern California as a Visiting Professor, details are in the First Semi-Annual Report (Fall 1986). Here I made contact with Tom Dickey, David Siegel, and Dale Kiefer. Conferring with these fine scientists allowed for productive forays into ocean optics from my earlier strong involvment with the optics of inland waters, partially supported by the USDA. A most rewarding aspect of this part of the contract period was the interest and generous cooperation given me by many others at USC, UCSD, UCSB, the old Visibility Lab., and Biospherical Instruments, Inc., San Diego.

One of the organizing themes of this research contract was the importance of modeling and investigating ocean optical phenomena from the point-of-view of the mean cosine of the average photon path of the submarine light field. This parameter is easily, but not routinely, measured as the ratio of the net downwelling irradiance and the scalar irradiance. The mean cosine parameter can be used to extract the true absorption coefficient from the exponential decay coefficient of the net downwelling irradiance. It is also an index of multiple scattering in the submarine light field. Furthermore, changes in this parameter can be used to quantify optical energy trapping—the increase of energy absorption in a layer or region where the average photon path is increased relative to other layers (Stavn, 1987). Such a situation can occur with augmented multiple scattering, multiple interreflections at the air/water interface, or wave focusing.

Data from an experimental optical mooring, set out by Biospherical Instruments, Inc. at Scripps Canyon and sampling the surface layers, immediately indicated a low value of the mean cosine parameter and thus a relatively large average photon path near the air/water interface. These values reported by C.R. Booth of Biospherical were much lower than the few values that had been previously reported for ocean water. Therefore optical

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energy trapping must be occurring in the surface layers of the ocean affected by wave focusing. Similar conclusions came from data supplied by Dale Kiefer where data on the exponential decay of the downwelling irradiance and the absorption coefficient of the surface layers were made available. These conclusions will be used for future planning of optical probes and determinations of the optimum mode of data filtering from the field. There is great potential here for the investigation of the storage of energy in the surface layers of the ocean and its exchange at the air/water interface. Overall these results argue for the collection of data on the mean cosine parameter on a routine basis.

Among the many problems associated with collecting optical data at sea is the horizontal position of the optical sensor platform. Ship motion and wave action combine to give optical measurements that are confounded with changes in depth and a tendency for the platform to tilt. Simple geometrical relations were developed that allow the absolute correction of the net downwelling irradiance to a horizontal reference plane if the angular deviation of the platform is known. The corrections to the net downwelling flux can put bounds on the possible values for downwelling and upwelling irradiances when data filtering is required. The advantage here is an absolute basis for correction rather than having to rely on arbitrary data filtering algorithms. The potential is for accurately determining the irradiant fluxes of the submarine light field where deviations of the light sensing platform from the horizontal can make a large contribution to the "noisy" data from which we attempt to extract meaningful light profiles.

Increasing familiarity with oceanic algorithms, facilitated by the people named above, stimulated me to investigate the optical properties of the water molecule. Certain commonly accepted oceanic algorithms make simplified assumptions about the optical properties of the water molecule. As with all simplified assumptions, this restricts the phenomena that can be investigated with such models and a quantitative study of the limitations on these assumptions was started.

After finishing at USC, I initiated a Visiting Professorship at NORDA (now NOARL) in Bay St. Louis Mississippi for eight months, details can be found in the First Annual Report (Summer 1987). My activities centered around interaction with Rudolph Hollman and Alan Weidemann in the Optical Oceanography Program. I continued work on light penetration and the optical properties of the water molecule, further demonstrating that the water molecule does not absorb a constant fraction of incoming energy, i.e. it is affected by multiple scattering and the average photon path. The effect of ignoring this varying absorption of energy in simplified algorithms is to underestimate the energy budget of the water molecule and overestimate the energy budget of dissolved/suspended matter. The error is severe in oligotrophic-low chlorophyll waters so that many algorithms proposed for ocean optics take a different form when applied to either low chlorophyll or high chlorophyll waters. I proposed that the mean cosine of the average photon path is necessary for determining the true optical characteristics of the water molecule, calculating an accurate energy budget, and predicting quantitatively the effects of simplified assumptions on optical energy budgets (Stavn, 1988).

About halfway through the tenure at NORDA (now NOARL) I began the development of the NOARL optical model with Alan Weidemann and a group of

fine FORTRAN programmers at the lab. In addition to an excellent technical staff, the administrative personnel at NOARL are qualified scientists who take a personal interest in purely scientific questions in addition to their normal administrative duties. These factors have made my work at NOARL particularly stimulating and rewarding. A simple initial version of the NOARL optical model predicted the quantitative importance of water Raman scattering using the recognized optical parameters of molecular water and quartz-like suspended material. These results provided one possible explanation for anomalies in the exponential decay coefficients (diffuse attenuation coefficients) determined from optical data sets collected for and by the US Navy in previous years. The anomalies occurred for longer wavelengths (520 nm +) where the calculated exponential decay of the light field was often less than the minimum which would be expected for molecular water. This sort of result can be explained as either light leakage around a blocking filter placed in front of the light sensor or internal emission of radiation from the hydrosol into the waveband of interest. The Monte Carlo simulation of the NOARL optical model provided a plausible explanation of these differences based on the internal radiant emission that could be generated by the Raman scattering cross section of the water molecule. One problem, however, with reasoning from the K coefficients or exponential decay coefficients is the multiplicity of factors that can decrease their magnitude. Definitive proof of water Raman emission had to await the deployment of the state-of-the-art optical instrument package under development by NORDA (NOARL) called the POSSY (Particle-Optical Sampling System). The proof of the presence of water Raman emission required measurements of the mean cosine of the average photon path of the submarine light field.

Contract Period 1987 - 1988

The following year (starting in August, 1987) I returned to UNCG to resume full-time academic duties and continue collaboration with the NOARL Ocean Optics Program. The details of the first half of the year are covered in the Second Semi-Annual Report (Fall 1987) I continued the work on light penetration and the optical properties of the water molecule utilizing the NOARL optical model. It was demonstrated it simple algorithms with non-varying absorption by the water molecule can estimate significant amounts of dissolved/suspended matter when none is actually present. An expanded version of the NOARL optical model was developed which can handle spectral variations of the contribution of water Raman scattering to the submarine light field. The varying contribution of water Raman scattering to the submarine light field is caused by spectral variations of the absorption coefficient of dissolved/suspended matter. These variations in the absorption of photons by components other than molecular water will create variations in the potential interactions of molecular water with the ambient photon field (Stavn and Weidemann, 1988b).

The second half of this contract year was spent in residence at UNCG and at Bay St. Louis, Mississippi for a summer of work at NORDA (NOARL). The details are covered in the Second Annual Report (Summer 1988). Simulations of water Raman emission were done with the expanded NOARL optical model at 520 nm. This wavelength (± 5 nm) was represented by a complete series of data on the downwelling and upwelling irradiances and the scalar irradiance from the Biowatt-NORDA cruise to the Sargasso Sea in the summer of 1987.

Thus a definitive set of mean cosine values was available for a routine optical analysis. The prediction of a decrease in the mean cosine to relatively low values, due to the nearly uniform Raman emission contributing to the flux at 520 nm, was confirmed with the Sargasso Sea data. The quantitative prediction of the magnitude of the mean cosine at 520 nm was also confirmed. A decrease in the mean cosine would not be observed if light leakage were present because the mean cosine would still be that of a relatively directional solar source of photons rather than that of a nearly uniformly emitted source of photons. This was proven in a region of the visible spectrum (520 ± 5 nm) where it is difficult to demonstrate water Raman emission because there is still significant solar flux occurring at this wavelength. A relatively large solar photon flux can mask water Raman activity and this activity is easier to demonstrate at longer wavelengths where the solar flux is absorbed relatively rapidly. Thus, the most efficient mode of verifying and quantifying internal radiant emission by the water molecule or other sources (e.g. fluorescence) is by the mean cosine parameter of the Three-Parameter model of the submarine light field (Stavn and Weidemann, 1988a, 1988b). Anomalies of K coefficients will always be confounded with the possibilities of light leakage or similar phenomena. Because of various mishaps during the Sargasso Sea cruise (including loss of the POSSY instrument), the data for other wavelengths in the longer wavelength region (550 nm, 589 nm) were not complete. However the measurements that were available (irradiance ratio at 550 nm and downwelling irradiance at 589 nm) did support the hypothesis of water Raman emission at these wavelengths (Stavn and Weidemann, 1988b).

Contract Period 1988 - 1989

The final year of this contract, a continuation beyond the original two year period, was spent in residence at UNCG with another summer working at NORDA (NOARL). Details for this period can be found in the Third Annual Report (Summer 1989). The NOARL optical model was used to simulate open ocean water types (Case 1 waters) from known optical parameters available in the literature. Such parameters included absorption coefficients for dissolved organics and particulate organics and the latest work on the absorption coefficients and volume scattering functions of major groups of algae. The purpose is to extend the simulations of irradiant flux to differing water types to determine derived optical parameters for which direct optical measurements are difficult or impossible. To be sure, the estimation of separate solar and Raman photon streams and their effects on light field parameters falls into this category of investigation. The primary interest for this simulation series was the effects of the highly asymmetrical volume scattering function of natural hydrosols on the upwelling and downwelling streams of radiant flux. The investigations were carried out at 440 nm so that water Raman scattering had a minimal effect on in-water optical properties. The result of the simulation was a demonstration that two-flow type models of radiant flux cannot be inverted in natural hydrosols (Stavn and Weidemann, 1989). An extension to the Two Flow model was proposed, incorporating the Three-Parameter model, which can be inverted (yielding at least partial information on inherent optical parameters).

Work also went forward on water Raman emission. Among the indicators of Raman emission activity (decreasing mean cosine, decreasing K coefficients, increasing R coefficients) is a decrease in the hydrosol absorption

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coefficient calculated from the submarine irradiance field. The simulations with the NOARL model demonstrated that the anomalies of the calculated absorption coefficient are quantitative indicators of the percentage of the irradiance field that results from internal radiant emission. The ability to determine this comes from the nearly uniform spatial emission of Raman photons, giving them an entirely different average photon path compared with the solar photons. The method, used with an independent determination of the hydrosol absorption coeficient, quantifies internal emission from all sources. In the most oligotrophic oceans the major source of photon emission will be water Raman scattering. Current work involves determining methods of partitioning the photon emission among water Raman scattering, chlorophyll fluorescence, and humic and fulvic acid fluorescence.

At present, I am working with the Academic Computer Center at UNCG for porting some of this work to the Cray Y-MP of the North Carolina Super Computer facility at the Research Triangle Park. This will expand the scope of the simulations possible with the NOARL optical model.

TECHNICAL REPORTS

First Semi-Annual Report/Progress Report, N00014-86-K-0606, Fall 1986.
First Annual Letter Report, N00014-86-K-0606, Summer 1987.
Second Semi-Annual Report/Progress Report, N00014-86-K-0606, Fall 1987.
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Third Annual Letter Report, N00014-86-K-0606/P00001, Summer 1989.

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